Environmentally-Friendly Kirigami Building Envelopes

Unknown Artists
Emily Spencer
Gray DeSimone

Advisor: Dr. Shu Yang

Abstract

Skyrocketing building cooling costs are only exacerbated by aesthetically-focused architecture. The current trend of all glass exteriors has negative consequences for buildings themselves as well as surrounding urban environments. Building envelopes are materials that can be applied to the exteriors of building to reinforce insulation properties. This project aims to explore one possible approach. Kirigami is a japanese art extremely similar to origami with the inclusion of cutting as well as folding. Using a kirigami framework our team selected optimal materials for a semi autonomous building envelope. With a proper design this envelope can open and close letting light in when necessary and blocking when not. This design will also come with the added benefit of water collection which will be used to open and close the envelope as well as for evaporative cooling. Findings showed maximizing the amount of edge area maximizes the amount of water collected by condensation. The material selected was an aluminum-coated PET, carrying the joint benefits of an insulating material with an active surface. This material was coated with an omniphobic PMHS layer to add hydrophobicity. Testing showed a proof of concept with effective water collection on an expanding and contracting envelope.

Introduction

Global urban populations are increasing while rural populations are declining. With this increase in city dwellers, buildings are being erected for people to live and work in. As a result massive amounts of energy are used to heat and cool these buildings throughout the year. The US department of energy found that 40% of energy costs in an average commercial building come from heating, cooling, and ventilation. This accounts for about 7.5% of total building costs.[1] At the same time, about 39.1% of residential energy usage is devoted to heating and cooling. The Department of Energy predicts residential energy use will decrease by 2040 due to increased efficiency of products and appliances. However commercial energy use is expected to increase by 12% in the same time period.

Despite the dire importance of resource conservation and sustainable living practices, many current trends and entrenched societal norms diverge from these ideals. One key example of this is current trends in urban building design. In the early construction, most large buildings had concrete exteriors with windows embedded. The current trend for buildings, however, (both business and residential) is large glass skyscrapers. The first glass skyscraper was designed in 1921 by architect Ludwig Mies Van Der Rohe, but the idea really took off in the first part of the 21st century as the standard for high-rise building design.[2] While giving occupants spectacular views of the outside, these buildings are also aesthetically pleasing to those on the exterior, often reflecting the sky surrounding them. However, glass skyscrapers are monstrously inefficient for a variety of reasons.

First, glass is a terrible insulator. These buildings require massive amounts of energy to heat and cool, which is only exacerbated when they are located in extreme climates. Walls have much less function than windows, a wall serves only to separate the outside from the inside. A window must do the same while also being transparent and possibly having to open/close in event of an emergency. It is no surprise that walls have a greater resistance to heat flow (or R-value) than a window would.[3] Walls with an insulating performance R-30 are considered normal today while the insulating performance of a window is typically around R-4. This varies, and recent technology has improved window's R values up to R-20 for triple-pane suspended film windows with krypton gas. However this level of complexity drastically increases the weight of the window and thus the load on the building. Windows can outperform walls in heating as

---

[1] http://needtoknow.nas.edu/energy/energy-efficiency/heating-cooling/
[2] https://www.bbc.com/news/magazine-27501938
[3] https://www.constructioncanada.net/windows-versus-walls-debunking-the-energy-myth/

some windows have a net energy gain by admitting more heat from the sun than is lost from conduction. And while this can sometimes be beneficial in cooler months, in warmer months this affect drastically increases cooling costs.

Another issue with glass is its reflectivity. Glass is naturally reflective, and glass used in building skyscrapers is often treated with a reflective coating. This coating can help increase privacy for residents and improve climate control inside of the building by reflecting some of the sun's rays. However this reflectivity causes real problems for the areas surrounding these buildings. The reflected rays bounce of the buildings and are absorbed by the concrete below, only intensifying the urban heat island effect. This causes densely populated urban areas to be 1.8-5.4 degrees Fahrenheit warmer in the summer than the surrounding suburbs.[4] The reflective nature of these new skyscrapers can even cause direct destruction to the landscape below, as was the case in 2013 when the London skyscraper "20 Fenchurch" melted a car parked across the street and caused the carpets in front of businesses in its shadow to catch fire.[5]

Even with the concerns over glass buildings being strong and well known, they continue to be built at an alarming rate. Nearly every new high rise building is designed in this style, and new ones are being erected every day. This sweeping trend of mostly glass skyscrapers will provide buildings with effective means of heating in the winter but leave these same buildings at a loss when cooling in the summer. With climate change causing more extreme temperature fluctuations and more intense seasons, this issue will only intensify in coming years.[6] This paired with population shifts towards warmer climates and cooling will become a much greater problem for large buildings than heating. The US Department of Energy defines heating degree days as the number of degrees increased inside a building multiplied by the number of days heating was used. This metric averaged to about 4,084 in the US in 2018.[7] That number is expected drop by about 4% in 2040 to 3,914. Conversely cooling degree days will increase in that same amount of time by about 0.4% from 1,418 to 1,648.

Research into methods for conserving resources and making our infrastructure more efficient will be of growing importance in coming decades. Overpopulation and climate change are poised to put a serious strain on our planet's natural resources. If left unchecked, the human population will choke itself to death in the name of economic progress by recklessly consuming resources until there is nothing left to sustain us. The

[4] https://www.epa.gov/heat-islands
[5] https://www.nbcnews.com/sciencemain/london-skyscraper-can-melt-cars-set-buildings-fire-8C11069092
[6] https://www.edf.org/climate/climate-change-and-extreme-weather
[7] https://www.edf.org/climate/climate-change-and-extreme-weather

stakes for creating more sustainable solutions to our current way of life couldn't be higher, with the health of our species and our planet on the line.

To curb the many problems presented by glass-fronted buildings we set out to design an environmentally friendly building envelope. Building envelopes function as physical separators between a building's conditioned environment and unconditioned exterior. On the exterior of a glass building an envelope could help shade the building's many windows from excessive solar heat. Additionally an effective envelope would work as an insulator in the winter time, preventing conductive heat loss through windows with low heat resistance.

Methods

Making use of kirigami allowed our building envelope to autonomously change its shape depending on the temperature outside or the angle of incident sunlight. Kirigami is a variation of the japanese art origami involving cutting of paper in place of simply folding. Seen below in Figure 1, kirigami in this context will involve patterned cuts in a material to create a shape that is expandable and retractable. There are many possible cut patterns in the art of kirigami and each one will allow our end product to reduce or expand its area by a different amount. On a large building an envelope that can compress to a small area and then be stored on a roof during a moderate-temperature day will be of great interest to building owners.

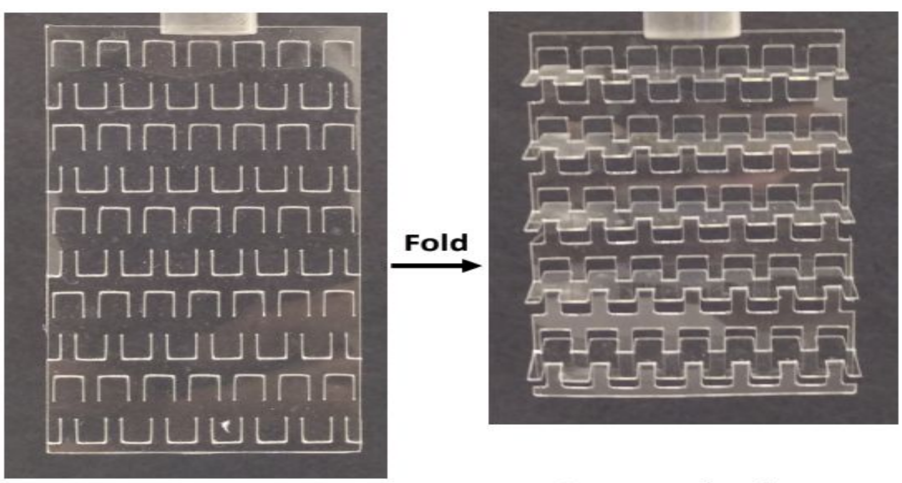

Figure 1: (Shu Yang 2018) Demonstration of Kirigami with basic rectangular shape

Previous work on kirigami building envelopes have shown that certain geometries are better than others when it comes to effective water collection. Preliminary testing has shown that rectangle patterns are more effective than triangle and arc shaped patterns in water collection (see Figure 2). Designs are made in Adobe Illustrator and then programmed into a Cricut Cutter for accuracy. Our first prototypes can be seen in Figure

4. These were cut into Tyvek paper, which is made of flashspun high-density polyethylene fibers for resistance to tears. Neither prototype was tested for water collection or movement as both were created simply to test geometries. The dimensions and spacing of the cuts was extremely important. If cuts are made too close together there will not be enough room for water droplets to properly nucleate and travel. On the other hand, because most water droplets tend to nucleate on the edges, cuts that are too far apart will leave the sample without adequate edge space for drops to form. Both spacing and geometry were crucial in optimizing the building envelopes for water transport.

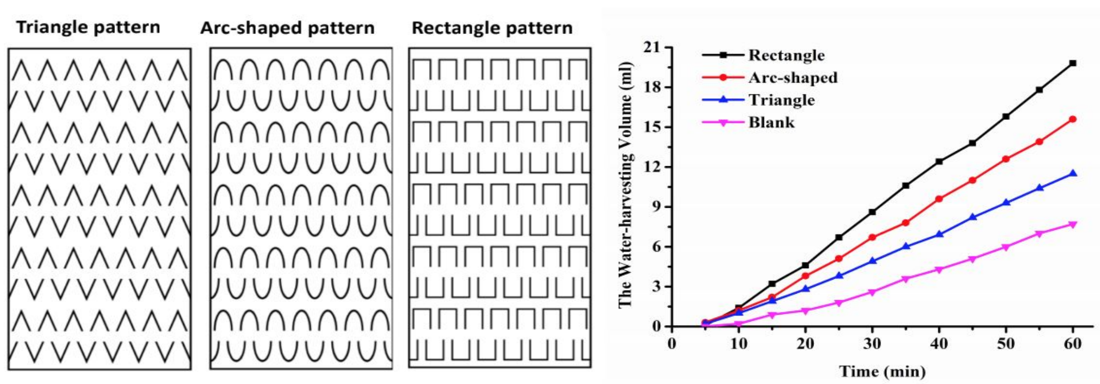

Figure 2: (Shu Yang 2018) The effectiveness of water collection for different cut patterns

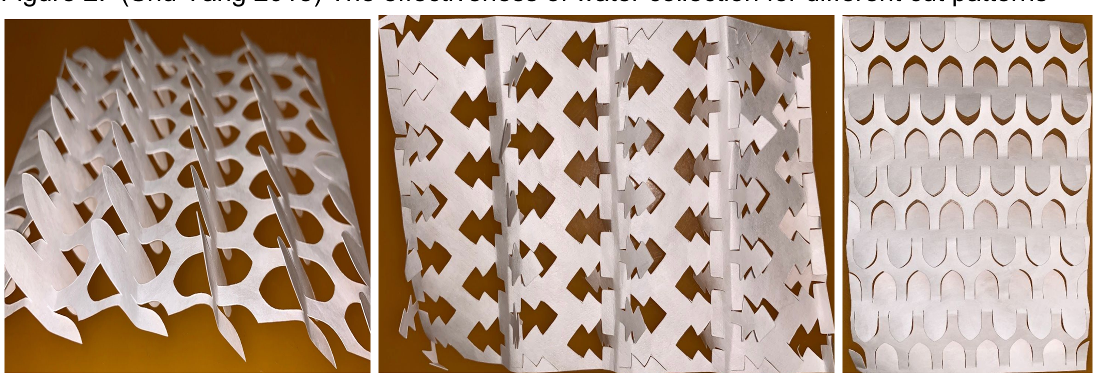

Figure 3: Paper prototypes for kirigami designs

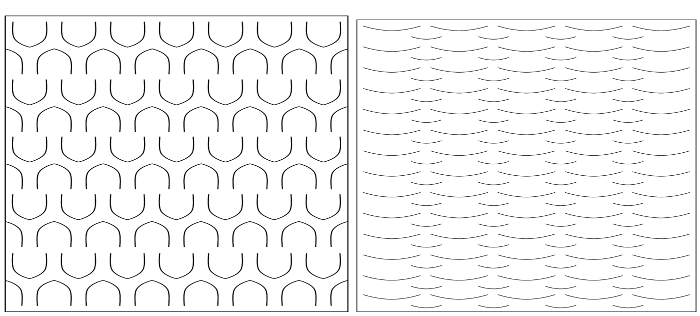

Figure 4: Adobe illustrator files of designs

Through an iterative design process we were able to select a cut pattern which would allow for a great amount of expansion and contraction. As seen in Figure 5 below when expanded, our envelop will take on a net-like appearance. Flat edges form during expansion which also provided the benefit of water collection.

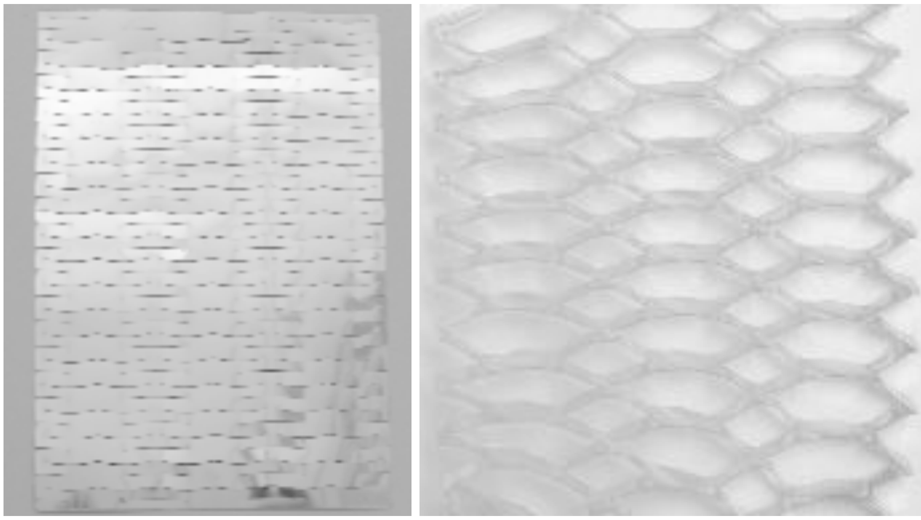

Figure 5: Final envelope design when closed (a) and open (b)

After we had finalized our design, materials selection for these envelopes still came with a unique set of challenges. To begin, strength and durability of the material was imperative to the success of the envelope. If the final product must be deployed over the surface area of a large building it must be able to withstand variable weather conditions depending on the urban climate. This was made more difficult simply by the nature of kirigami which includes several intentional cuts which could allow simple tears to form and propagate down already existing lines. We were tasked with finding a material that provided strength and durability while remaining lightweight and flexible.

The next property that was taken into account was insulation. If these envelopes are to be used all year round they must function are great insulators to both keep heat out in the summertime and the opposite in the winter. Ideally resistance to heat flow would be comparable to that of a simple window however this may not be possible given cuts in the material for added properties.

There was also the concern of choosing a material with a treatable surface. As mentioned above a hydrophobic coating on the exterior of our envelope will be incredibly important for its success. In order to successfully apply our coating we needed a material with a surface that allowed for layers of coating.

A final issue came in the form of reflectivity of the material. As mentioned above one of the main reasons glass buildings have become increasingly popular is the reflectivity that glass provides. As well as creating an interesting aesthetic which often reflects the surrounding skyline, reflective buildings prevent heating by absorbing very little sunlight. Ideally our building envelopes would share some of these reflective properties to prevent the sun's rays from even reaching the exterior of the building. Some of the detriments of reflectivity were mentioned above however when this property is applied to an envelope it will not have the same effect as it does on the outside of a building. The problem that occured in London involving the melting of a car will not happen as curvature of an envelope will vary with the wind and cannot concentrate into a single beam in the same a building exterior can. Additionally concerns of overheating the surrounding city will hopefully be mitigated by the evaporating water that collects through condensation.

As shown below in figure 6 we settled on aluminum-coated polyethylene terephthalate or PET as our final material. This makes fantastic candidate as the PET itself will act as an insulator, one of the most important factors of the envelope itself. PET is often recycled into thermal insulation for buildings. Additionally PET is durable while still being lightweight meaning it can hang from the exterior of a building without tearing or breaking while not putting excess strain on the outside of the building. The aluminum coating provides several benefits. Aluminum provides an active surface upon which a coating can be applied. Without the aluminum we would not be able to successfully apply our omniphobic surface layer. Aluminum also provides the favorable feature of a reflective coating on the exterior of the envelope. Both Al and PET are recyclable materials making both of them abundant and friendly to the environment.

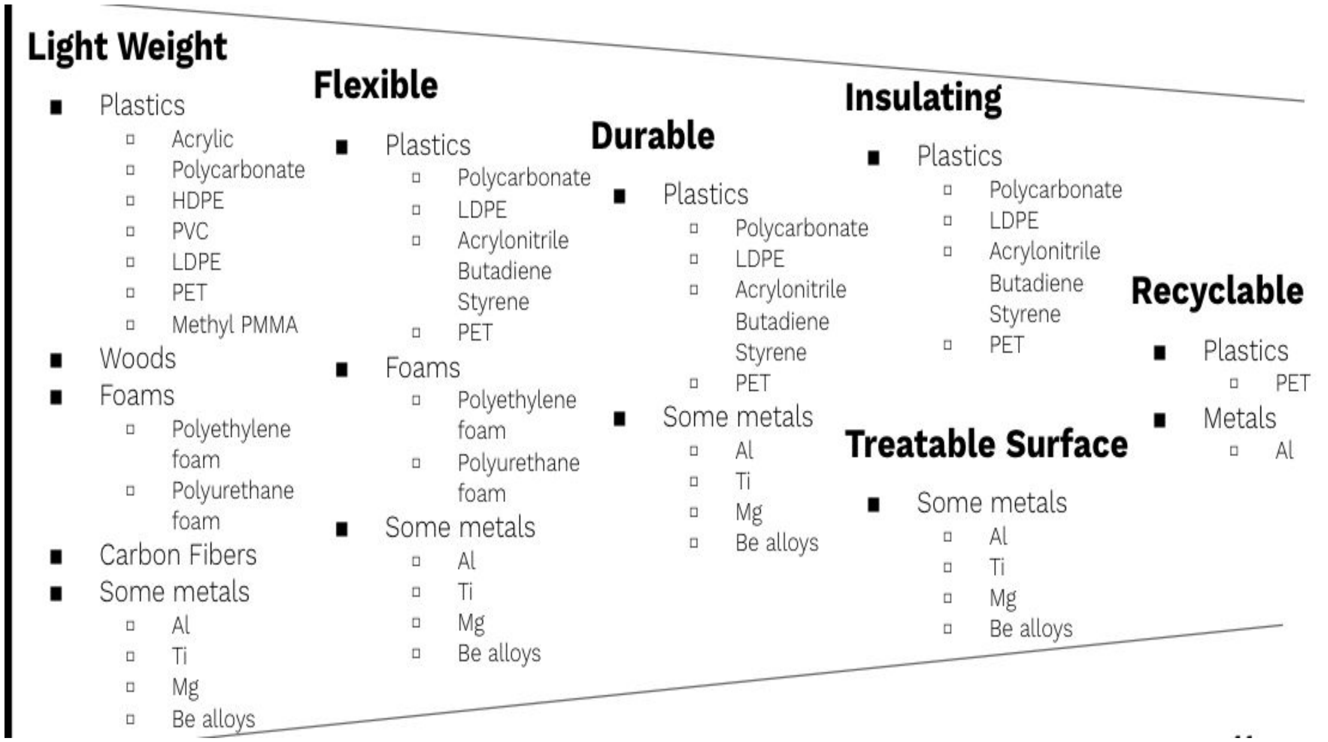

Figure 6: Materials selection candidates and restrictions

To select the ideal omniphobic coating for the envelope we had to go through a similar materials selection process. We decided on an omniphobic surface layer because omniphobic materials keep the surface clean of debris and allows for the formation of larger water drops with low contact angles. We went with a PMHS because it bonds easily to the activated Al surface of the Al coated PET. The specific PMHS we chose, HMS-991 is inexpensive, durable, and safe for the environment. Two important things to consider when creating something to goes on the outside of a building.

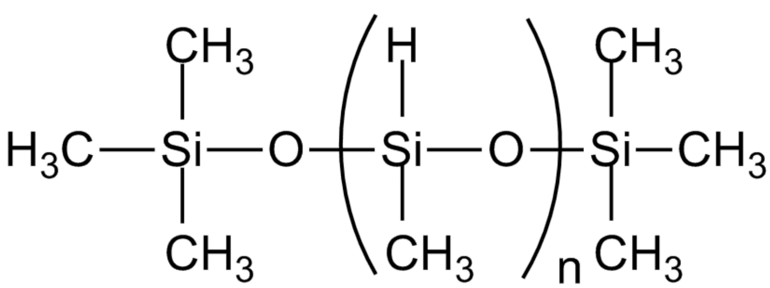

Figure 7: Molecule of PMHS

PMHS was applied using a dip coating method to ensure a uniform layer on the exterior. Before application the surface was extensively cleaned to remove any glue remnants from the cricut cutter. It was then put into an oxygen plasmator to create a hydroxide layer on the coating to allow for easier attachment. The PMHS coating then immediately applied. Finally the sample was placed into a vacuum oven at 80°C for 12 hours to ensure the two layers were properly bonded. Once a coating was successfully applied and droplet tested we began testing for water harvesting. This was done in a lab setting using a simple humidifier device. A tube was connected to the humidifier and aimed directly at the sample being tested. From there several still shots are taken and water is collected below to determine the most effective design.

Figure 8 below demonstrates the water harvesting device and setup.

Figure 8: The rig holding the sample and the water collection device

Results

Below is a chart listing the contact angle of our PMHS-coated, Al-coated PET compared to the contact angle of regular PET. It is evident that the contact angle has increased within our sample indicating a greater amount of hydrophobicity. This means larger water droplets are being collected onto our surface and more water is being collected as well.

	PET	Al Coated PET w/ PMHS Coating
Static Angle	75.0°	103.4° ↑
Advancing Angle	82.8°	110.9° ↑
Receding Angle	52.0°	83.8° ↑

Table I: Contact angles for Treated and Untreated Al-Coated PET

Water harvesting also proved successful. Using a collection system and our humidification technique we were able to determine the amount of possible water collection as well as the rate of water collection. Data was collected for both the sample in its collapsed state and in its expanded state. A chart of this water collection versus time is shown in figure 9 below.

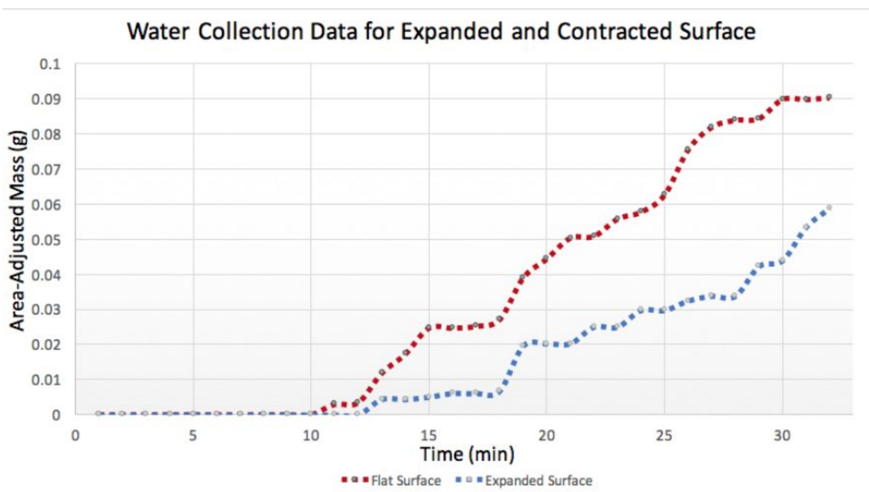

Figure 9: Contact angles for Treated and Untreated Al-Coated PET

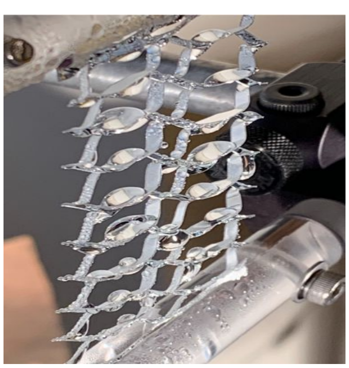

Figure 10: Water droplets formed on the open envelope

Figure 10 above shows an important feature of our envelopes. When expanded large water droplets for on the shelf-like features that are created. Eventually as enough of these water droplets form they begin to propagate and fall down to envelope to be collected.

Discussion and Conclusion

Solutions to transition society into a greener and more sustainable future will require technology that can modify existing infrastructure. Kirigami building envelopes have the potential to make glass skyscrapers more energy efficient. This project demonstrated a proof-of-concept of these envelopes. A unique geometry was developed and an ideal materials system was determined. This envelope design performs well when opened and closed. When opened the design holds on to much of the water it condenses, which is ideal for evaporative cooling. When closed the smooth system allows for rapid transfer of water down the material. This would be ideal for saturating a hydrogel that could open the envelope autonomously. A building envelope like this one has the potential to significantly decrease the energy usage of large glass buildings.

Future work to continue this project would involve additional trials to add to the data on water collection, and development of the hydrogel system. Additional steps would be needed to get these building envelopes ready for market that are beyond the scope of this project.

References

Chen, Huawei, et al. “Ultrafast Water Harvesting and Transport in Hierarchical Microchannels.” *Nature Materials*, vol. 17, no. 10, 2018, pp. 935–942., doi:10.1038/s41563-018-0171-9.

“Could the Era of Glass Skyscrapers Be over?” *BBC News*, BBC, 27 May 2014, www.bbc.com/news/magazine-27501938.

“Extreme Weather Gets a Boost from Climate Change.” *Environmental Defense Fund*, www.edf.org/climate/climate-change-and-extreme-weather.

Figure 1. Yang, Shu 2018, *LRSM building -University of Pennsylvania Campus,* digital image, University of Pennsylvania, viewed 12, November 2018

Figure 2. Yang, Shu 2018, *LRSM building -University of Pennsylvania Campus,* digital image, University of Pennsylvania, viewed 12, November 2018

Figure 5. Yang, Shu 2018, *LRSM building -University of Pennsylvania Campus,* digital image, University of Pennsylvania, viewed 12, November 2018

Figure 6. Yang, Shu 2018, *LRSM building -University of Pennsylvania Campus,* digital image, University of Pennsylvania, viewed 12, November 2018

“Heat Island Effect.” *EPA*, Environmental Protection Agency, 27 Sept. 2018, www.epa.gov/heat-islands.

Hiddleston, Sarah. “Harvesting Fresh Water from Desert Air.” *Nature Middle East*, Aug. 2018, doi:10.1038/nmiddleeast.2018.66.

Ju, Jie, et al. “Bioinspired One-Dimensional Materials for Directional Liquid Transport.” *Accounts of Chemical Research*, vol. 47, no. 8, 2014, pp. 2342–2352., doi:10.1021/ar5000693.

Lallanilla, Marc. “This London Skyscraper Can Melt Cars and Set Buildings on Fire.” *NBCNews.com*, NBCUniversal News Group, 3 Sept. 2013, www.nbcnews.com/sciencemain/london-skyscraper-can-melt-cars-set-buildings-fire-8C11069092.

Singh, Narendra, et al. “Omniphobic Metal Surfaces with Low Contact Angle Hysteresis and Tilt Angles.” *Langmuir*, vol. 34, no. 38, Dec. 2018, pp. 11405–11413., doi:10.1021/acs.langmuir.8b02430.

"The National Academies Presents: What You Need to Know About Energy." *Fossil Fuels* -, needtoknow.nas.edu/energy/energy-efficiency/heating-cooling/.

"Windows Versus Walls: Debunking the Energy Myth." *Construction Canada*, 21 Nov. 2016, www.constructioncanada.net/windows-versus-walls-debunking-the-energy-myth/.

Yurtoğlu, Nadir. "Http://Www.historystudies.net/Dergi//Birinci-Dunya-Savasinda-Bir-Asayis-Sorunu-Sebinkarahisar-Ermeni-isyani20181092a4a8f.Pdf." *History Studies International Journal of History*, vol. 10, no. 7, 2018, pp. 241–264., doi:10.9737/hist.2018.658.